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Measurement of the Ratio of the $Z/\gamma^*(\rightarrow e^+e^-)+\geq n$ Jet Production Cross Sections to the Total Inclusive $Z/\gamma^* \rightarrow e^+e^-$ Cross Section in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a study of events with Z bosons and hadronic jets produced at the Tevatron in $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV. The data sample consists of $\approx 14,000$ $Z/\gamma^* \rightarrow e^+e^-$ candidates from 343 pb^{-1} of integrated luminosity collected using the DØ detector. Ratios of the $Z/\gamma^*(\rightarrow e^+e^-)+\geq n$ jet cross sections to the total inclusive $Z/\gamma^* \rightarrow e^+e^-$ cross section have been measured for $Z/\gamma^*+\geq 1$ to 5 jet events. Our results are found to be in good agreement with a next-to-leading order QCD calculation and with a tree-level QCD prediction with parton shower simulation and hadronization.

Preliminary Results for Spring 2005 Conferences

Leptonic decays of the electroweak gauge bosons, $W^{\pm}$ and Z, produced in association with jets are prominent processes at hadron colliders. Measurements of $W/Z+ \geq n$ jet cross sections are important for understanding perturbative quantum chromodynamics (QCD) calculations and Monte Carlo (MC) simulation programs capable of handling particles in the final state at leading order (LO), or in some cases, next-to-leading order (NLO). Furthermore, the associated production of W/Z bosons with jets represents a serious background to other interesting physics processes within or beyond the Standard Model (SM). For example, the most promising modes for a light Higgs discovery at the Tevatron are those where the Higgs is produced in association with a vector boson $(W/Z)H$ with $(W/Z) \rightarrow$ leptons and $H \rightarrow b\bar{b}$, and the $W+$ jets channel is important to top-quark studies. Many extensions of the SM predict new particles which decay into SM gauge bosons and are accompanied by jets.

In this study, we present the first measurement of the ratios of the $Z/\gamma^{*}(\rightarrow e^{+}e^{-})+ \geq n$ jet production cross sections to the total inclusive $Z/\gamma^{*} \rightarrow e^{+}e^{-}$ cross section for the jet multiplicities $n \geq 1-5$ jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. These results are based on 343 pb^{-1} of data accumulated by the DØ detector.

The elements of the DØ detector [1] of primary importance to this analysis are the uranium/liquid-argon sampling calorimeter and the tracking system. The DØ calorimeter has a transverse granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ forming projective towers, where η is the pseudorapidity ($\eta = -\ln[\tan(\theta/2)]$, θ is the polar angle with respect to the proton beam), and ϕ is the azimuthal angle. The calorimeter has a central section covering pseudorapidities up to ≈ 1.1, and two end calorimeters that extend coverage to $|\eta| \approx 4.2$. The tracking system consists of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively.

The data sample for this analysis was collected between April 2002 and June 2004. Events from $Z/\gamma^{*} \rightarrow e^{+}e^{-}$ decays were selected on line with a combination of single-electron triggers, based on energy deposited in calorimeter towers ($\Delta\eta \times \Delta\phi = 0.2 \times 0.2$). Final off-line event selection was based on run quality, event properties, electron, and jet criteria.

In the off-line analysis, events were required to have a reconstructed vertex with longitudinal position within 60 cm of the detector center. Electrons were reconstructed from electromagnetic (EM) clusters in the calorimeter using a simple cone algorithm. The two highest-p_T electron candidates in the event, both having transverse momentum $p_T > 25$ GeV, were used to reconstruct the Z boson candidate. Both electrons were required to be in the central region of the calorimeter $|\eta_{det}| < 1.1$ with at least one of them firing the trigger(s) for the event. The electron pair was required to have an invariant mass near the world average Z boson mass, 75 GeV $< M_{ee} <$ 105 GeV.

To reduce background contamination, mainly from jets faking electrons, the EM clusters were required to pass three quality criteria based on shower profile: (i) the ratio of the EM energy to the total shower energy had to be greater than 0.9, (ii) the lateral and longitudinal shape of the energy cluster had to be consistent with those of an electron, and (iii) the electron had to be isolated from other energy deposits in the calorimeter with isolation fraction $f_{\rm iso} < 0.15$. The isolation fraction is defined as $f_{\rm iso} = [E(0.4) - E_{\rm EM}(0.2)]/E_{\rm EM}(0.2)$, where $E(R_{\rm cone})$ ($E_{\rm EM}(R_{\rm cone})$) is the total (EM) energy within a cone of radius $R_{\rm cone} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ centered around the electron. Additionally, at least one of the electrons was required to have a matching track and the track transverse momentum had to be close to the transverse energy of the EM cluster. A total of 13,893 candidates passed the selection criteria.

Jets in the events were reconstructed off line using the "Run II cone algorithm" [2] which combines particles within a cone of radius $R_{\rm cone} = 0.5$. Spurious jets from isolated noisy calorimeter cells were eliminated by cuts on the jet shape. The transverse momentum of each jet was corrected for offsets due to the underlying event, multiple $p\bar{p}$ interactions, and noise, for out–of–cone showering, and for detector energy response as determined from the missing transverse energy balance of photon–jets events. Jets were required to have $p_T > 20$ GeV and $|\eta| < 2.5$. Jets were eliminated if they overlapped with the electrons coming from the Z boson within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. Jet losses due to this separation cut from the Z boson electrons were estimated as a function of the number of associated jets using a Z+jet PYTHIA [3] MC sample.

The efficiencies for trigger, electron track-match, reconstruction and identification were determined from data, based on a "tag-and-probe" method. Z candidates were selected with one tight electron (tag) and another electron (probe) with all other cuts applied except the one under study. The fraction of events with the probe electron passing the requirement under study determines the efficiency of a given cut. The overall trigger efficiency for Z candidates was found to be $> 99\%$. The electron reconstruction and identification efficiencies were measured as a function of azimuth angle and p_T, and the average efficiency was found to be $\approx 89\%$. The track-match efficiency was measured to be $\approx 77\%$. The average electron reconstruction, selection, trigger, and track-match efficiencies were examined as a function of jet multiplicity. No significant variations of the efficiencies were observed, except for the track-match efficiency where adjustments were made to accommodate its multiplicity dependence.

The kinematic and detector geometric acceptance for electrons from Z/γ^{*} decays in the mass region of 75 GeV $< M_{ee} <$ 105 GeV was determined as a function of jet multiplicity. For the acceptance calculation of the inclusive Z/γ^{*} sample, an inclusive PYTHIA MC sample was used. The inclusive PYTHIA events were weighted so that the p_T distribution of the Z boson in the MC agreed with data. For the jet-multiplicity dependence of the acceptance calculation, the ALPGEN [4] $Z+n$ leading-order parton generator was used, with the evolution of partons into hadrons carried out by PYTHIA. This procedure represents a partial higher-order correction to tree-level diagrams. All MC samples were processed through full detector simulation.

The reconstruction and identification efficiency of jets was determined from a data-tuned PYTHIA MC sample with full detector simulation. A scaling factor was applied to the MC jets to adjust their reconstruction and identification efficiency to that of data jets as compared using the "Z p_T−balance" method. In events selected with Z candidates, a search for a recoiling jet opposite to the Z boson in azimuth was performed. The probability of finding a recoiling jet as a function of the Z p_T was measured in data and MC. The ratio of these probabilities in data and MC defines the scaling factor that was applied to the MC events. After applying the scale factor, the jet reconstruction and identification efficiency was determined by matching particle (i.e. hadron) level jets to calorimeter jets. The efficiency was parameterized as a function of particle jet p_T, where the p_T values were smeared with the data jet energy resolutions.

The main source of background to the Z/γ^* signal comes from QCD events and it was estimated for each jet multiplicity. For the $Z/\gamma^*+\geq 0-2$ jet samples, a convoluted Gaussian and Breit-Wigner function was fitted to the Z resonance, assuming an exponential shape for both the QCD background and the Drell-Yan component of the signal. In case of the $Z/\gamma^*+\geq 3$ jet sample, the size of the QCD and Drell-Yan components was estimated based on the sidebands of the di-electron invariant mass spectrum. In each case, an inclusive Z/γ^* PYTHIA MC was used to disentangle the QCD component from the Drell-Yan contribution. The background contributions for higher jet multiplicity samples were estimated by extrapolating an exponential fit to the QCD background of the $0-3$ jet multiplicity bins.

The cross sections as a function of jet multiplicity were corrected for jet reconstruction and identification efficiencies, and for event migration due to the finite jet energy resolution of the detector. The correction factors were determined using a $Z+$ jets PYTHIA MC sample, tuned to match the measured jet multiplicity distribution in data. The sample only contained particle level jets (i.e. no detector simulation). The p_T of the particle jets were smeared with the data jet energy resolutions. Subsequently, jets were removed from the sample, probabilistically, and according to the measured jet reconstruction efficiencies. The ratio between the two inclusive jet multiplicity distributions (the generated distribution and the one with the jet reconstruction/identification efficiency and energy resolution applied), determined the unsmearing correction factors.

The fully corrected $Z/\gamma^*+\geq n$ jet production cross sections are normalized with respect to the inclusive Z/γ^* cross section for the mass region 75 GeV $< M_{ee} <$ 105 GeV.

$$R_n = \frac{\sigma_n}{\sigma_0} = \frac{\sigma[Z/\gamma^*(\rightarrow e^+e^-)+\geq n \text{ jets}]}{\sigma[Z/\gamma^*(\rightarrow e^+e^-)]} \tag{1}$$

Table I summarizes the cross section ratios for the $Z/\gamma^*+\geq 1$ to 5 jet samples. Systematic uncertainties include variations in the jet energy scale, jet reconstruction and identification efficiency, electron-jet overlap correction, and jet energy resolution. They also take into account uncertainties in the variation of efficiencies for trigger, electron reconstruction, identification, and track matching as a function of jet multiplicity. The statistical uncertainties include contributions from the number of candidate events, background estimation, acceptance, efficiencies, and unsmearing correction.

Figure 1 shows the fully corrected measured cross section ratios for $Z/\gamma^*+\geq n$ jets as a function of n, compared to two QCD predictions. MCFM [5] is a NLO calculation up to $Z+2$ parton processes. The CTEQ6M set was used for parton distribution functions (PDF) and the factorization and renormalization scales were set to $\mu^2_{F/R} = M^2_Z + p^2_{TZ}$. The ME-PS theory is based on MADGRAPH [6] $Z+n$ LO Matrix Element (ME) predictions using PYTHIA for parton showering (PS) and hadronization, and a modified CKKW [7] method to map the $Z+n$ parton event into a parton shower history [8]. The ME-PS predictions [9] were produced with MADGRAPH tree level processes up to 3 partons, and have been normalized to the measured $Z/\gamma^*+\geq 1$ jet cross section ratio. The CTEQ6L PDF was used and the factorization scale was set to $\mu^2_F = M^2_Z$. The renormalization scale was set to $\mu^2_R = p^2_{Tjet}$ for jets from initial state radiation and $\mu^2_R = k^2_{Tjet}$ for jets from final state radiation. Both QCD predictions agree well with our data.

Figure 2 compares jet p_T spectra of the n^{th} jet in $Z/\gamma^*+\geq n$ jet events to MC predictions based on ALPGEN $Z+n$ LO partonic predictions using PYTHIA for parton showering and hadronization, with CTEQ5L PDF and $\mu^2_{F/R} = M^2_Z + \sum p^2_{Tjet}$. The MC events have been passed through full detector simulation. Reasonable agreement can been seen over a wide range of jet transverse momenta.

In summary, we have presented the first preliminary results of the ratio of the $Z/\gamma^*(\rightarrow e^+e^-)+\geq n$ jet production cross section to the total inclusive $Z/\gamma^* \rightarrow e^+e^-$ cross section from $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The ratios of the measured cross sections were found to be in good agreement with MCFM and a tree-level QCD prediction with parton shower simulation and hadronization.

TABLE I: Cross section ratios with statistical and systematic uncertainties for different inclusive jet multiplicities.

Multiplicity (≥n jets)	$R_n = \frac{\sigma_n}{\sigma_0}$ [$\times 10^{-3}$]	Statistical Uncertainty [$\times 10^{-3}$]	Systematic Uncertainty [$\times 10^{-3}$]
1	119.1	±3.3	+17.2 / -16.2
2	18.1	±1.3	+4.5 / -4.3
3	2.6	±0.52	+0.90 / -0.89
4	0.61	±0.28	+0.29 / -0.27
5	0.42	±0.30	+0.42 / -0.24

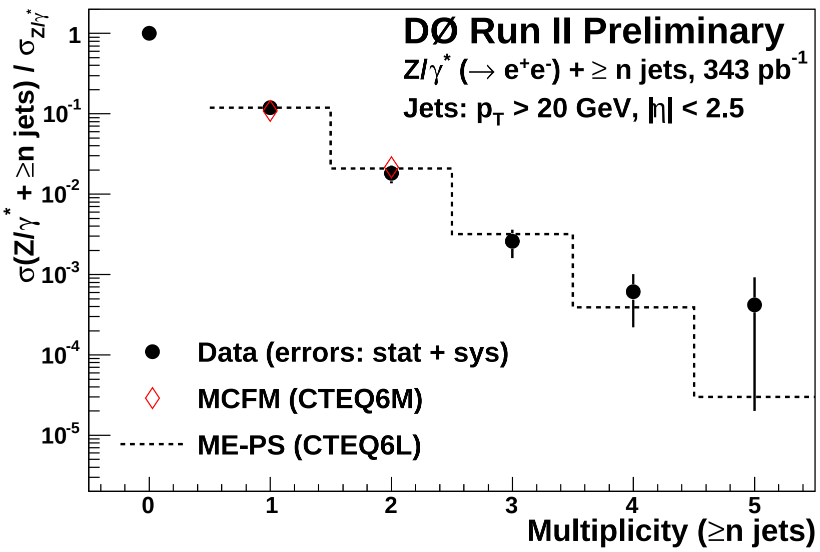

FIG. 1: Ratios of the $Z/\gamma^*(\rightarrow e^+e^-)+\geq n$ jet cross sections to the total inclusive $Z/\gamma^* \rightarrow e^+e^-$ cross section versus n. The errors on the data include the combined statistical and systematic uncertainties. The line represents the predictions of LO Matrix Element (ME) calculations using PYTHIA for parton showering (PS) and hadronization, normalized to the measured $Z/\gamma^*+\geq 1$ jet cross section ratio. The open diamonds represent the MCFM predictions.

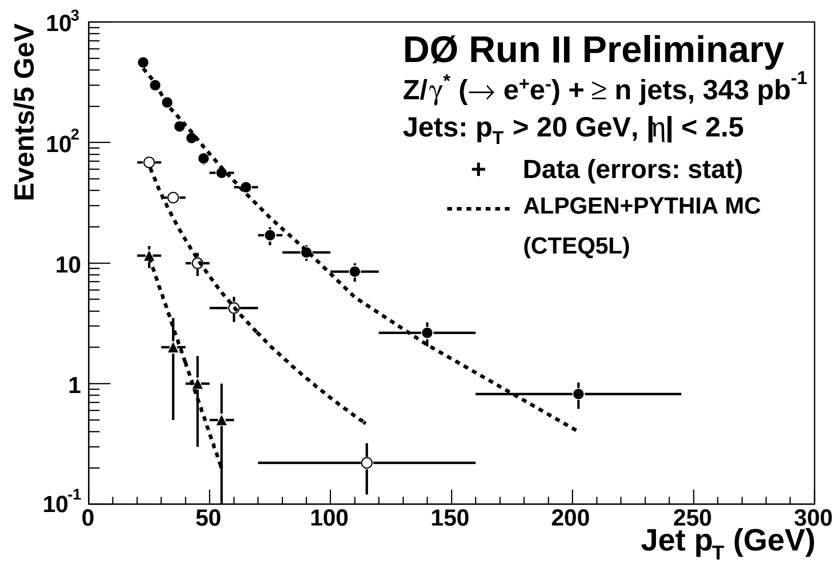

FIG. 2: Data to theory (ALPGEN+PYTHIA) comparison for the highest p_T jet distribution in the $Z+\geq 1$ jet sample, for the second highest p_T jet distribution in the $Z+\geq 2$ jet sample and for the third highest p_T jet distribution in the $Z+\geq 3$ jet sample. The errors on the data are only statistical. The MC distributions are normalized to data.

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